Argonne NATIONAL LABORATORY

Challenges for a detector at a 100 TeV hadronic collider for Higgs physics

S. Chekanov (ANL)

CPAD, October 5-7 (Texas, Arlington)

August, 2015

This talk is not about:

- Higgs physics at 100 TeV
- Reviewing detector concepts
- Suggesting technology
- Detailed Monte Carlo simulations
- Reviewing work of others (almost true)

image by J Sundqvist

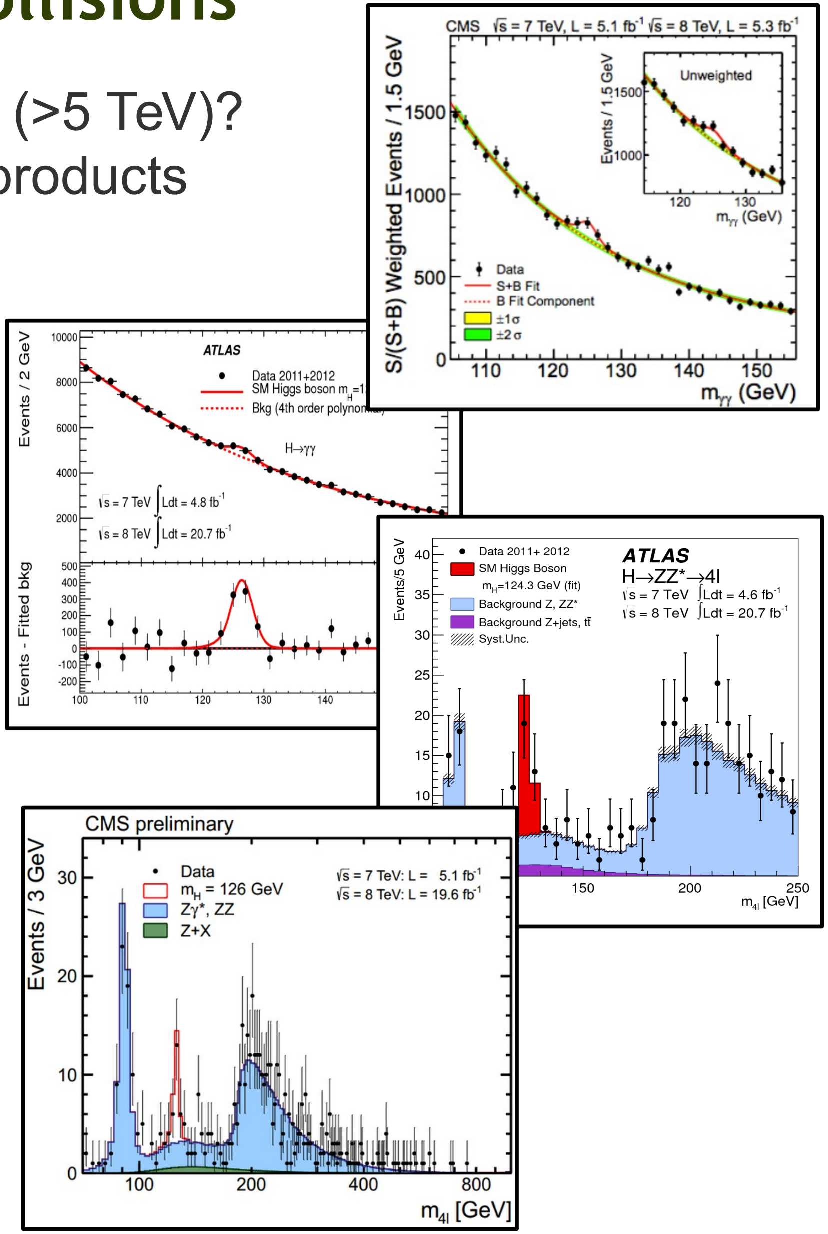
Foster discussion on detector requirements for Higgs physics & challenges that may lead to breakthrough technology for detectors in future

Beyond the LHC. 100 TeV pp collisions

→ Is the mass scale beyond the LHC reach (>5 TeV)?
→ Large masses → large energy of decay products

Higgs boson plays a central role:
- **discovery tool for new physics**
- **confronting the SM theory with data**

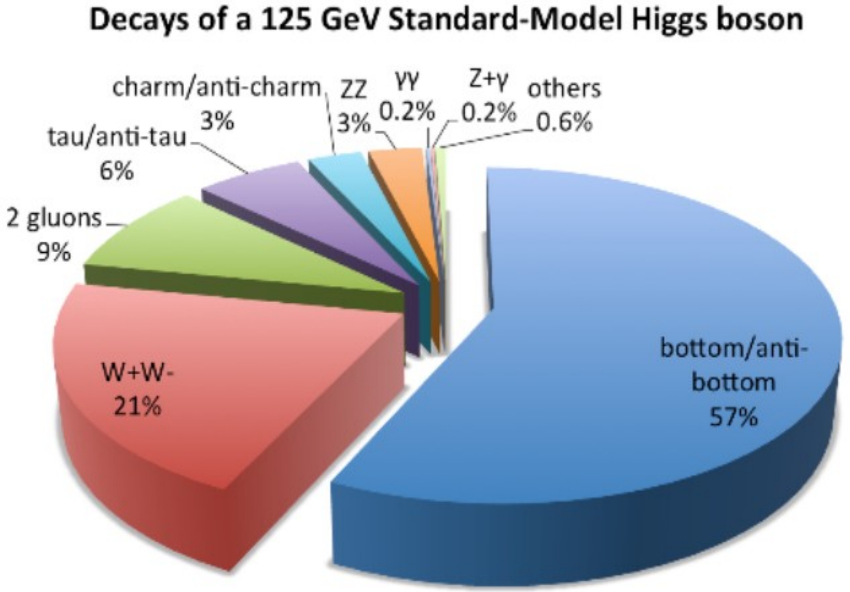
- **QCD tests in the Higgs sector**
- **Properties, Higgs couplings**
- **Higgs self-couplings measurements**
- **Searches for new decays**
- **Search for additional Higgs particles**
- **Rare decays (muons, hadrons)**
- **….**

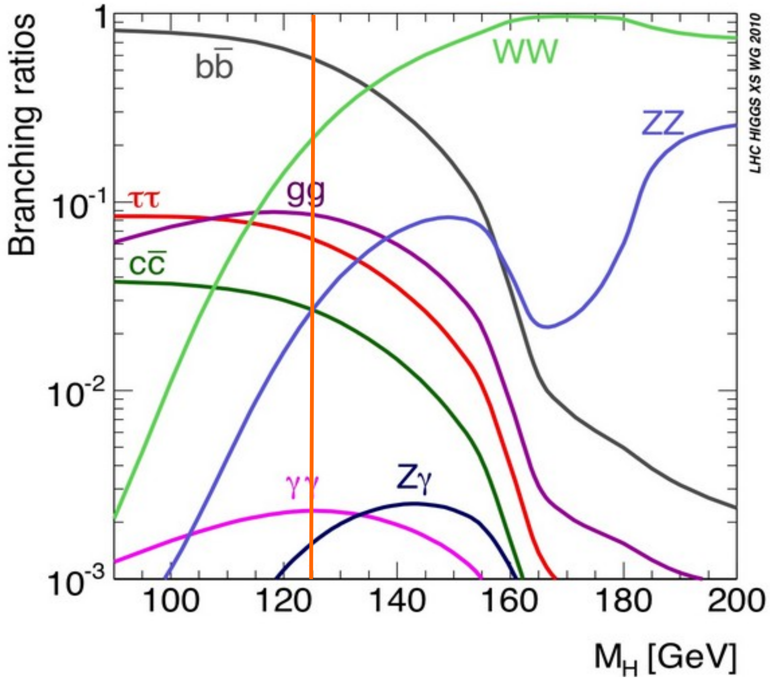


Instrumentation aspects

Higgs at M=125 GeV probes almost all detector performance issues for almost any known particle:

μ, e, γ, tau, top, light-quark jets, b-jets, Z, W,J/Phi, phi(1020)





Detector requirements

- Identification and precise measurements of photons, muons, electrons, tau's in multi-TeV regions & high-pileup environment
- Precise measurements of high-pT jets up to tens TeV (including b-jets)
- Measurement of missing transverse energy

Detector requirements → instrumentation choices

- "Technique **A** improves measurement **B** by **X%**"
  - how to set detector requirements?

- "Unless **A** is improved by **X%**, measurement **B** cannot be done"
  - stronger case for new design & technology
  - at the beginning of such studies

SSC, etc.

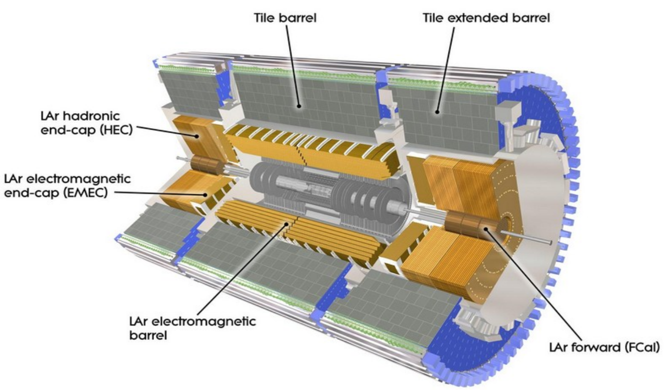
FCC etc.

LHC

Present: ATLAS & CMS

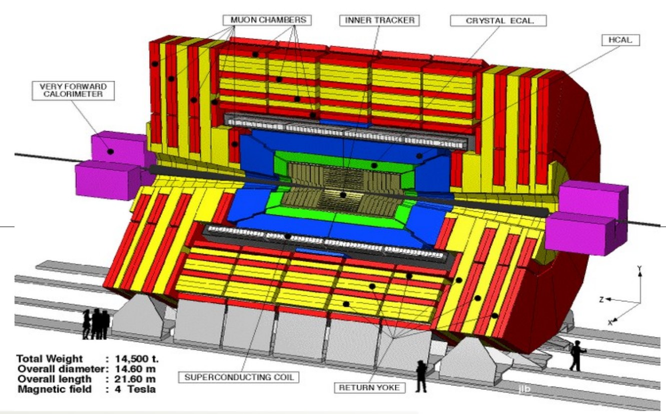
ATLAS

- CAL behind solenoid
  - Longitudinal segmentation
  - Angular measurements
  - Good energy resolution for jets
  - High granular
  - Radiation resistance
- Tracking:
  - silicon pixels + strips
  - TRT
- Muon spectrometer (RPC&MDT)
  - stand-alone capabilities (toroid)



CMS

- CAL before solenoid
  - Fast response (<100 ns)
  - High granular
  - Less radiation resistance
  - Good energy resolution (e/γ)
  - Brass + scintillator (HCAL)
- Tracking:
  - silicon pixels + strips (all silicon)
  - better momentum resolution
- Muon spectrometer (RPC& DTC)
  - requires good tracker



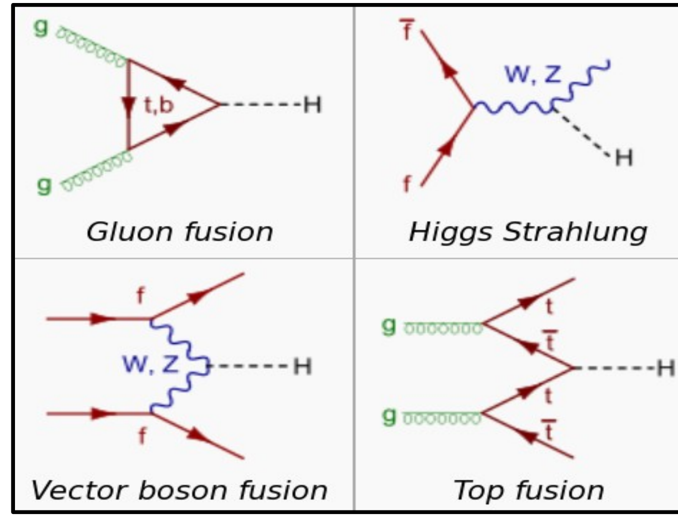
Baseline parameters for 100 TeV

https://fcc.web.cern.ch/Pages/Hadron-Collider.aspx

Version 1.0 (2014-02-11)	LHC	HL-LHC	FHC-hh
c.m. Energy [TeV]	14		100
Circumference *C* [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Arc filling factor	0.79		0.79
Straight sections	8		12
Average straight section length [m]	528		1400
Number of IPs	4		2 + 2
Injection energy [TeV]	0.45		3.3
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	171 34
Total / inelastic cross section [mbarn]	111 / 85		153 / 108
Number of bunches at - 25 ns - 5 ns	2808		10600 (8900) 53000 (44500)
Bunch population N_b [10^{11}] - 25 ns - 5 ns	1.15	2.2	1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	3.75	2.5	2.2 0.44

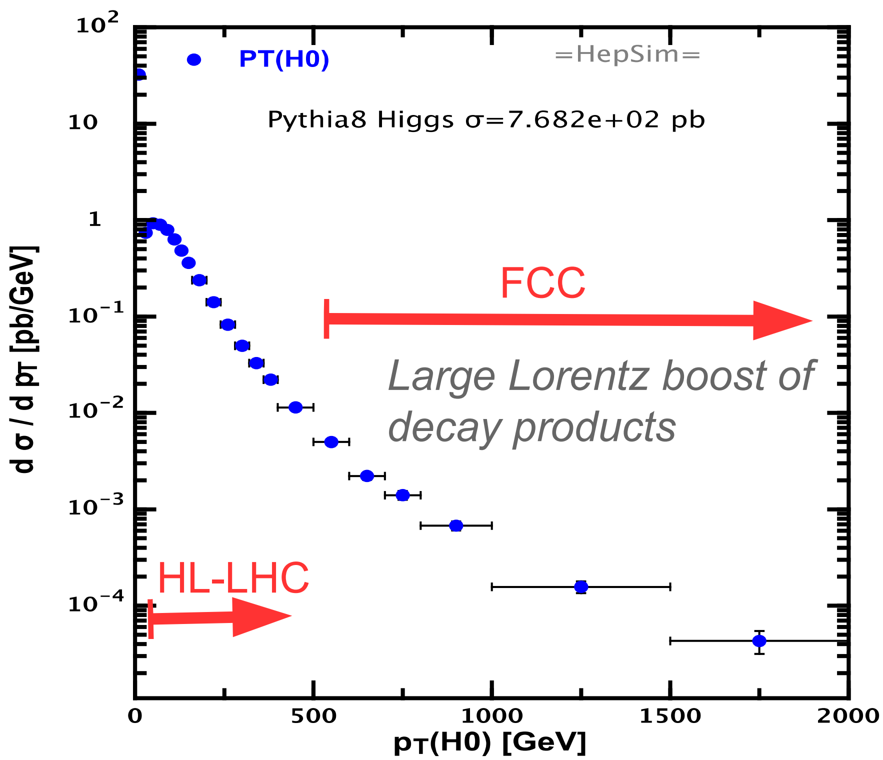
Standard Model (SM) Higgs

Business as usual: TeV scale SM Higgs



wikipedia

100 TeV pp

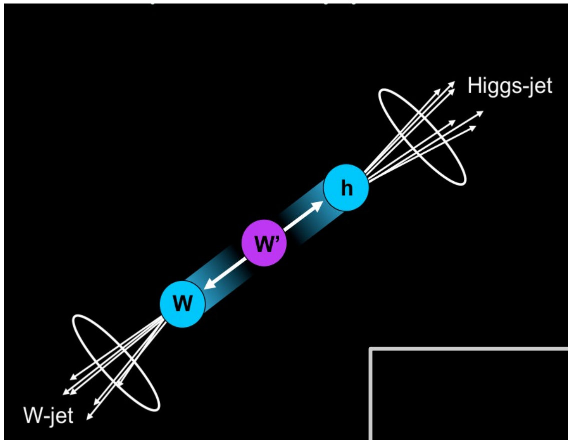


~100,000 Higgs / ab^{-1} for pT>1 TeV at LO

100 TeV detector should be designed for SM Higgs in the range pT(H)~0.5 - 2 TeV

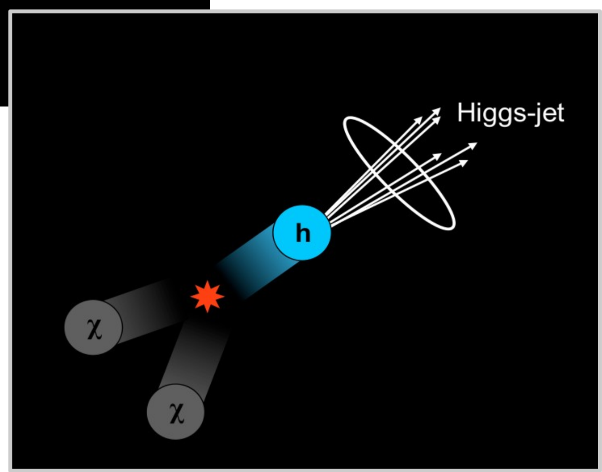
pT(H)>0.5 TeV → separation between decay products (b, γ, e/mu, etc.) < 10 degree → smaller than a typical hadronic jet with R ~0.4

Higgs as a window for new physics at 100 TeV



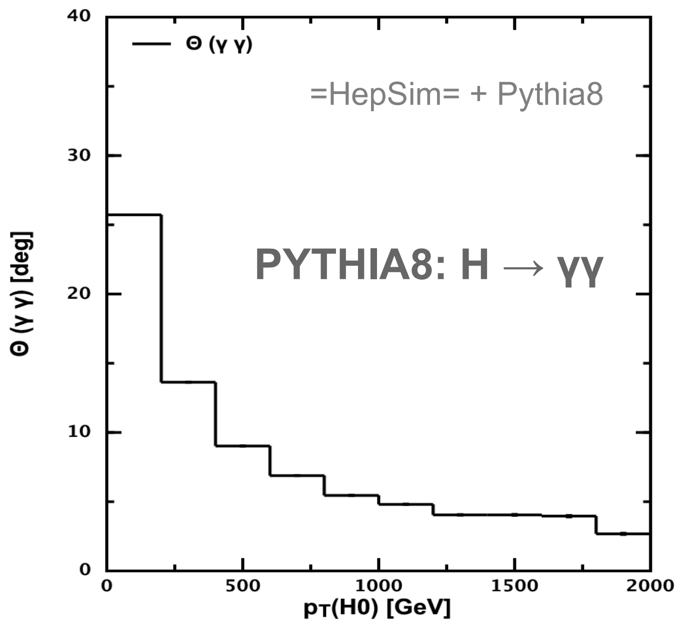
From. B Tweedie

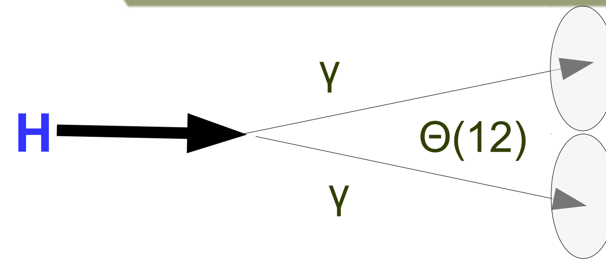
- 100 TeV collider will hunt for M~20-30 TeV particles that may decay to Higgs
- The detector must be optimized to reconstruct Higgs at **pT~10 TeV**



How bad is this for Higgs reconstruction in the "golden" decay channels: $\gamma\gamma$, Z^*Z, W^*W, $\tau\tau$, $b\bar{b}$?

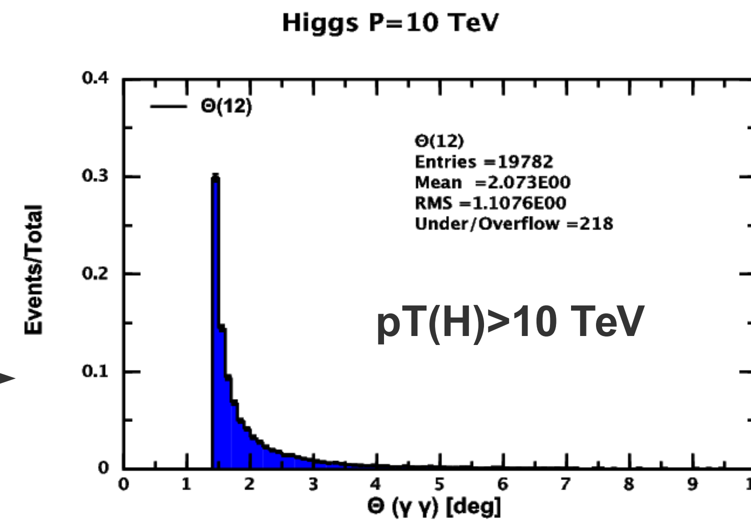
Boosting H → γγ





Two photons should be: isolated and M(γγ)~125 GeV

LHC experiments:
R=0.3-0.4 isolation to reduce hadronic background

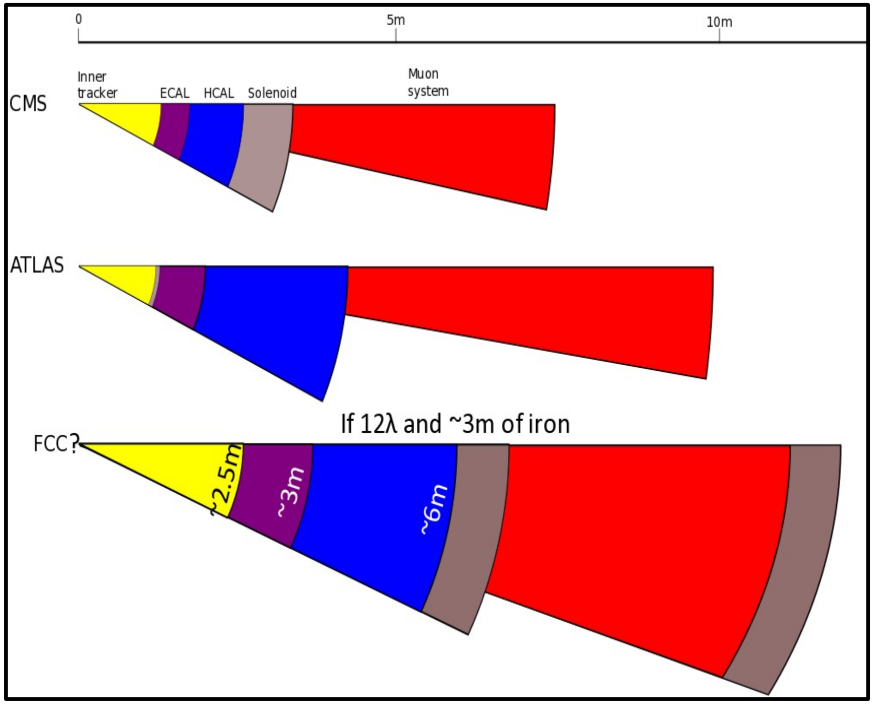


Two-photon separation in the Lab frame
(a calculator for rest frame decays+Lorentz boost)

<u>Angle between γ's</u>:
~ 5 deg for pT>2 TeV (→ "SM regime")
~ 1.5 deg for pT>10 TeV (→ "BSM regime")

<u>Instrumental goals:</u>
- identify 2 photons separated by 1 degree
- reject $\pi^0 \rightarrow \gamma\gamma$ background at the same time!

"1 degree rule" for ECAL FCC



C.Barnet, C.Helsens

To resolve 2 photons separated by 1 degree, we should have at least 2 ECAL cells between → cell size 0.5 deg (or better!)

Assuming 2.5 m distance from VTX,
0.5 deg translates to 2 cm cell size for ECAL

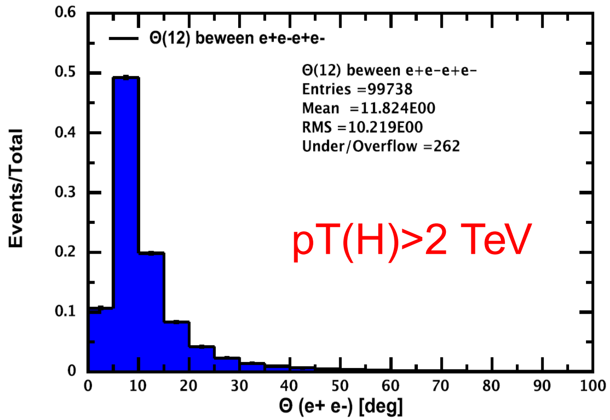
Standard paradigm:
Transverse cell sizes for 90% energy containment ~ **Moliere radius (M_R)**

	M_R (cm)
Liquid argon:	10
Lead tungstate (PbWO4):	2
Lead (Pb):	1.6
Fe	1.7

Standard approach: use ~2 cm cell size and satisfy "cell size< M_R" requirement

Do something else and deal with out-of-cell leakage effects. Digital calorimeter?
Can we use 2-cell veto for γγ? Is the resolution enough to build M(γγ) ~ 125 GeV?
→ **requires a full MC simulation**

Higgs → Z*Z → 4e

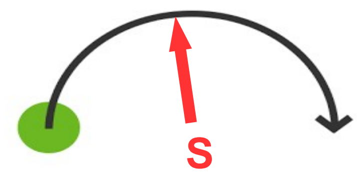


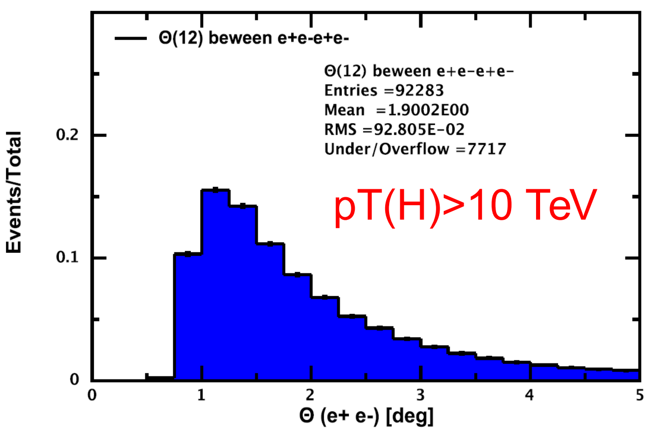
ECAL: from kinematics (neglect B-field)
- pT>10 TeV → 4 electrons in the cone of ~ 1 deg
- 2 cm cell (0.5 deg) is not enough to identify electrons

Challenging!

Assume CMS tracking with pixel size 100-150 μm
1.1 m, B=3.8 T → **sagitta= 90 μm**

$\sigma / pT = 20\ \%$ at pT=2 TeV





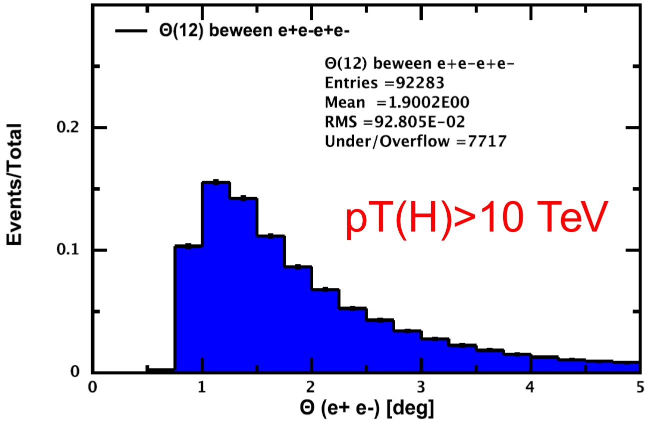
→ 40% resolution on M(4e)
→ 125 GeV overlaps with 90-GeV peak

$s = 0.3\ B\ {}^*L^2 / 8\ pT$

Tracking resolution should be improved at least by a factor 10 to get acceptable resolution on invariant masses for pT(H)>2 TeV
Example: 1 μm pixels if B and L are the same as for CMS

To identify 4 electrons, look at EM cluster from 4 electrons in ECAL
Can we apply substructure variables?

H → Z*Z → 4e (continue)



s ~ $L^2 B$ → increase B .. but better L!

FCC-hh:

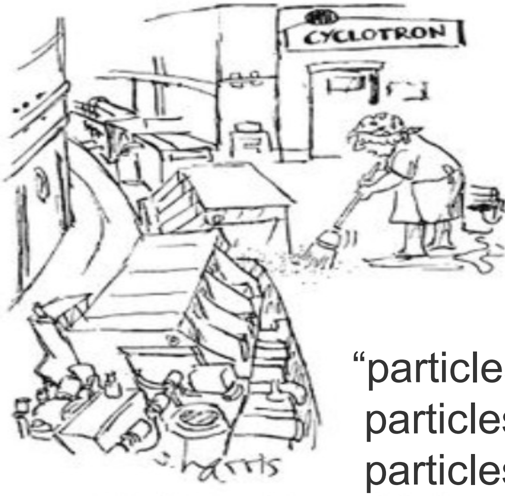
6 T Magnetic field, 2.5 m outer radius, CMS pixel size:
→ 0.7 mm sagitta for 2 TeV tracks
→ achieving similar resolution as for CMS for pT=200 GeV

4 tracks < 1 deg can be resolved assuming ~10 μm pixels

The proposed baseline for FCC pixel size is 5 μm
(W. Riegler, Sep. FCC meeting)

Typical pixel size for digital cameras ~2-6 μm

Small pixel sizes and L (x2.5) will help to fight high occupancies, multiple interactions and pileup (expected up to 2000 interactions per beam crossing)

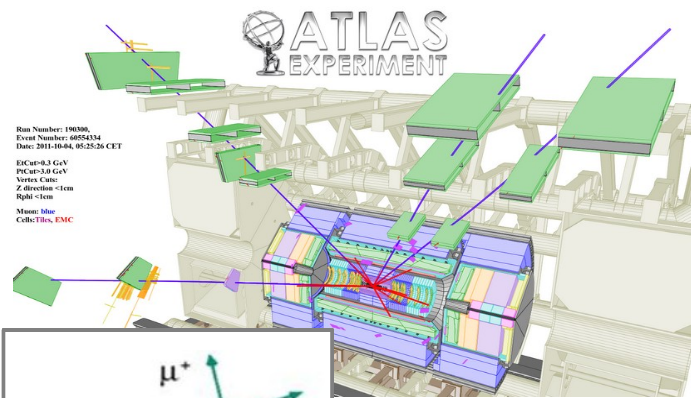


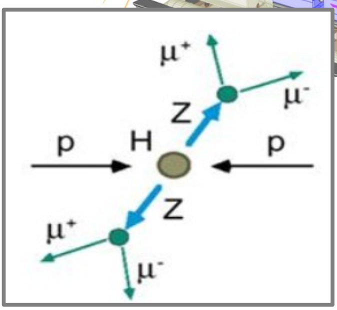
"particles, particles, particles..."

www.pinterest.com

Much depends on future technologies. Cost scaling expected by 2018

Muons. $H \rightarrow Z^*Z \rightarrow 4\mu$ (or $2e2\mu$) or $H \rightarrow 2\mu$





Kinematics:

pT(H)>10 TeV $\rightarrow$ 4 muons with pT~2 TeV in the cone of ~ 1 deg

ATLAS example (best case):
Sagitta ~ 500 μm for 1 TeV, Δσ ~50 μm
Spatial resolution < 50 μm

$\rightarrow$ 10% resolution for 1 TeV muon (~15% for pT~2 TeV)
$\rightarrow$ 30% smearing on invariant mass M(4μ) for pT(μ)>2 TeV

Aiming for ~10% resolution on M(4μ) means 5% resolution for 2 TeV muons

<u>Options:</u>
$\rightarrow$ Increase muon spectrometer size by ~50% (~ L*L)
$\rightarrow$ Increase the B field by ~ 100% (~ B)
$\rightarrow$ Decrease cell size by a factor 2

H $\rightarrow$ muons look more promising than γγ and 4e channels

FCC-hh muon spectrometer (CMS-like design)

The return field is 2.45T

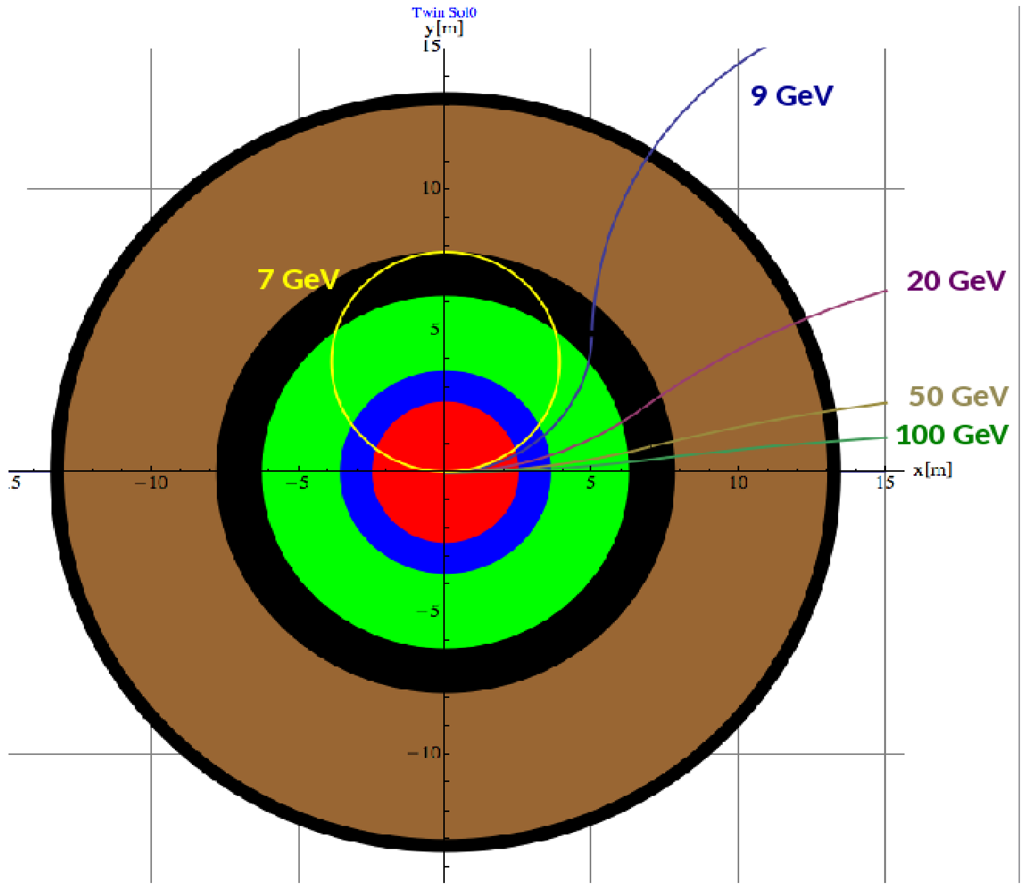
No muons below 7 GeV
(maybe use HCAL to recover)

Measuring over the 5m leverarm with stations of sig=50um resolution:

$dp_T/p_T = sig*p_T/(0.3*B*L^2)*8$

→ **20% @ 10TeV**

CMS sagitta measurement in the muon system is limited to dp_T/p_T = 20% due to multiple scattering alone.

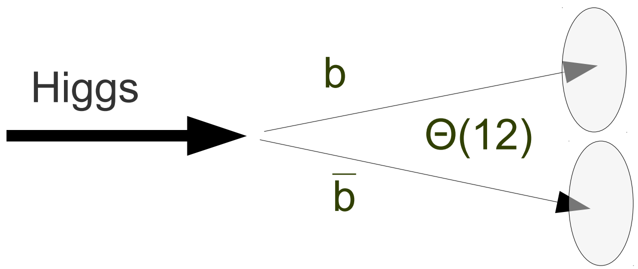


From W. Riegler. FCC meeting, Sep 16, 2015

Surface > 5000 m²

Muons are not MIPs at > 1 TeV!
Use calorimeter to help with reconstruction

H $\rightarrow$ jets ($b\bar{b}$ and associated jet production)



Just kinematics:
pT(H)>2 TeV ~ 5 deg separation
pT(H)>10 TeV~ 1 deg separation

Single boosted jet from $b\bar{b}$ and with jet mass M~125 GeV

.. standard jets (R~0.4-0.5). No large R-jets!
.. full of secondary vertices
.. soft muons
.. should leverage tracking and muon spectrometer

To use boosted jet techniques (trimming, filtering etc) to improve jet mass resolution, we need high-granular calorimeter

Challenges for HCAL

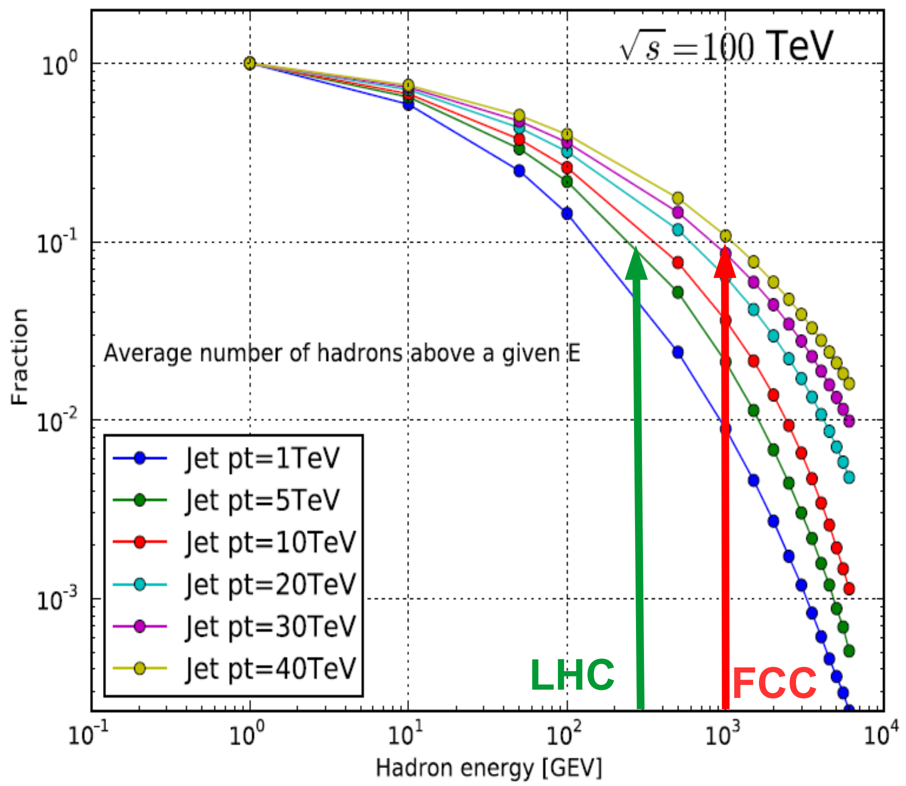
- Sufficient depth to avoid energy leakage outside the calorimeter
- Energy resolution with a constant term C~3% and below
- Longitudinal segmentation for 3D clusters
- Cell energy range ~0.2 - 20,000 GeV
  - must be extended by a factor 10 compared to existing HCAL
- Cell segmentation to allow for boosted technique
- Extended coverage η~6 is designed

Discussed at

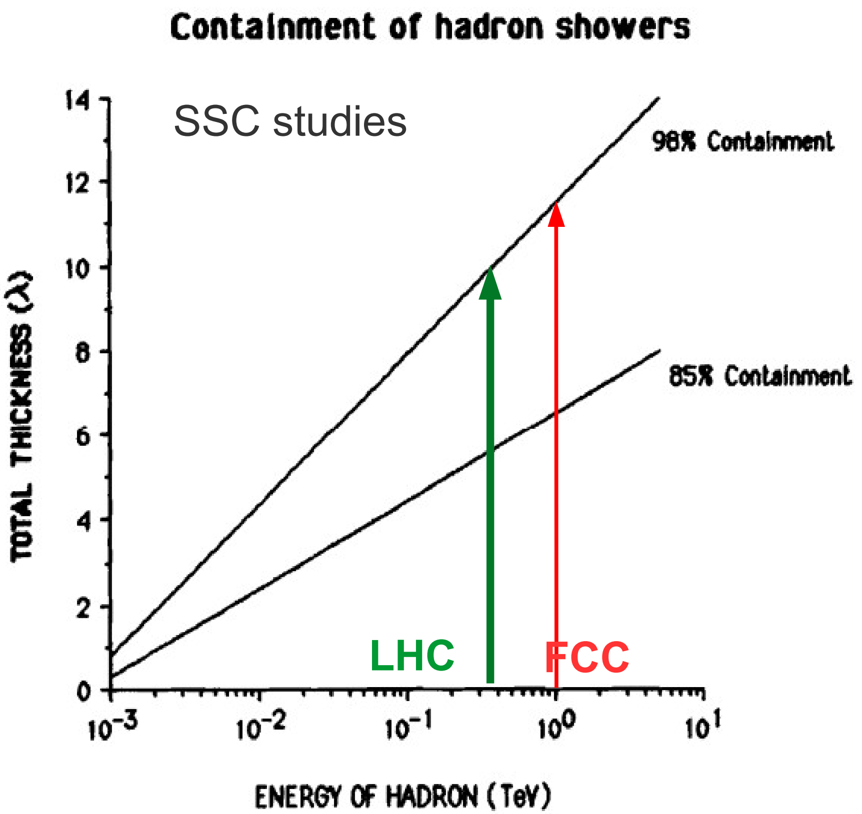
Estimating HCAL depth

Leading particles in high-pT jets

C.Helsens,C.Solans



http://lss.fnal.gov/conf/C860623/p355.pdf



pT(jet)>30 TeV: ~10% will be carried by 1 TeV hadrons (~9 hadrons/jet)
12 λ is needed to contain 98% of energy of a 1 TeV hadron
G4 simulation agrees with calculations for SSC (.. 1984 Gordon&Grannis. Snowmass)

Energy resolution

Performance of calorimeters improves with energy

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a – stochastic/sampling term,
b - electronic noise term
c - constant term

Single hadrons:

ATLAS: $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\%$

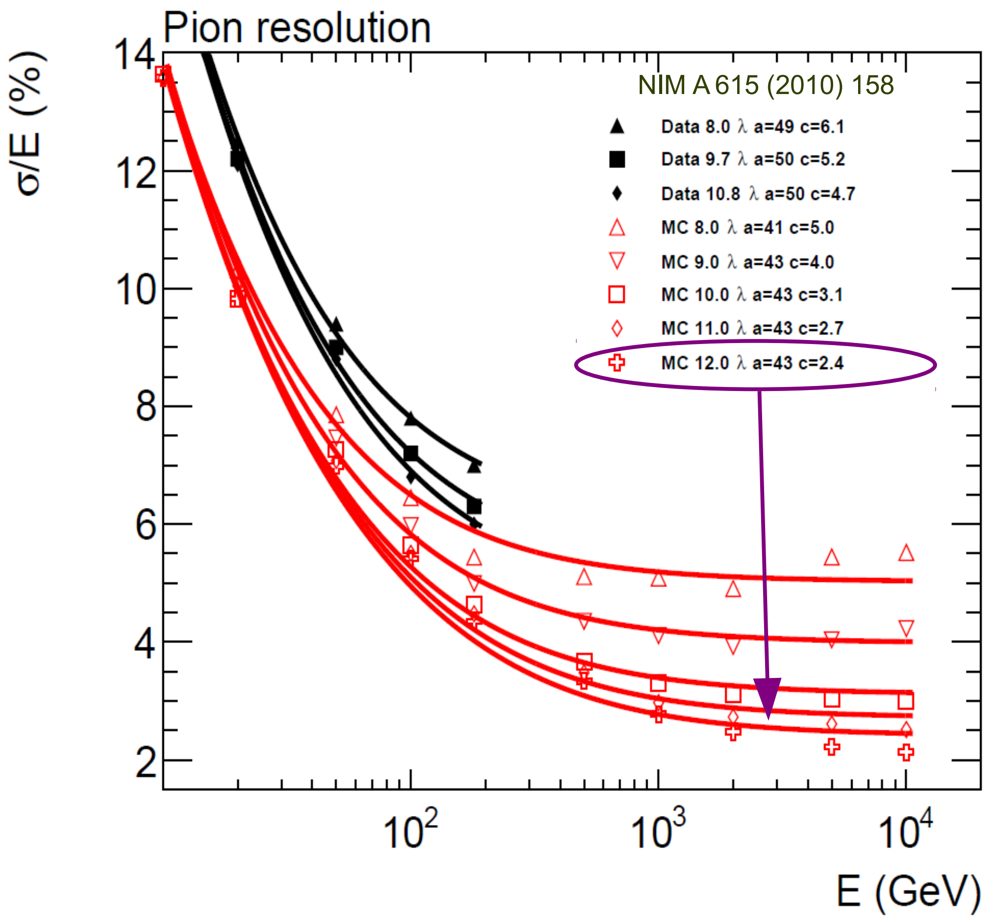
CMS: $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\%$

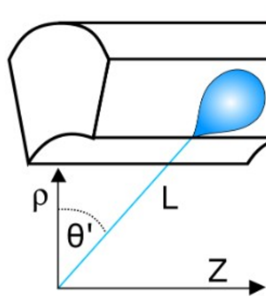
(small noise term for both)

pT(jet)~1 TeV: 50% contribution from the constant term
pT(jet)>5 TeV: Constant term dominates

Reduction of the constant term requires solutions for:
dead material, longitudinal and lateral energy leakage, non-uniformity calibration, transition region, etc.

Resolution for single pions





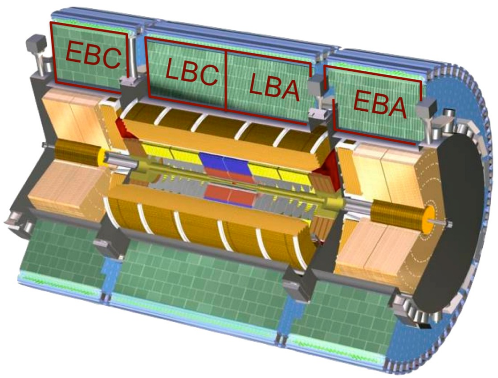
- Geant4 TileCal inspired simulation based on FTFP_BERT
- Calculate single-particle resolution
- Stochastic term is close to 45%/√E
- Constant term improves by ~20% with increase of 1 lambda
- Constant term c~2.5 is achievable

C.Solans

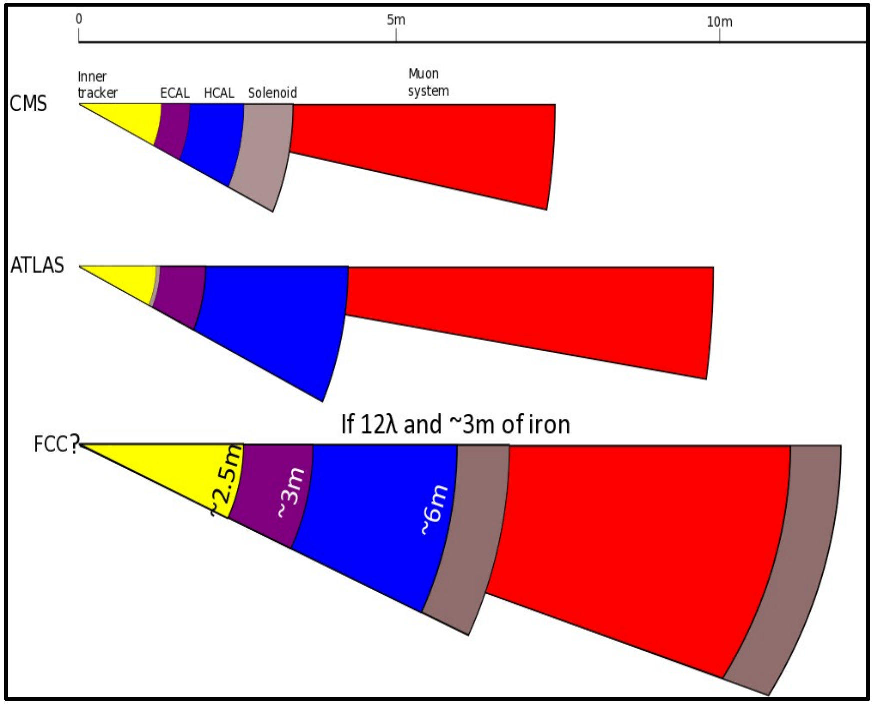
https://indico.cern.ch/event/404924/

Calorimeter segmentation: from LHC to FCC

HCAL (Tile)



- **ATLAS (best case for HCAL) :**
  - HCAL (TileCal) has 64 modules in φ (0.1 rad) and η=0.1 in the central region
  - ECAL has x4 better segmentation
  - Cell size ~22 cm (2.28 m from IP)
- **22cm means Δφ=0.06 rad for 3.5 m from IP**
  - ~ x2 better Δφ segmentation
- **Increasing segmentation by x4, x6 or more?**
  - but interaction length λ for Fe,Pb ~16 cm
  - large out-of-cell leakage expected
- **Calorimeter with <5 cm cell sizes requires detailed Geant4 simulation.**
- **What will we gain in reducing cell sizes?**
- **How to make the decision on segmentation based on physics?**
  - look at fast detector simulation



Substructure variables

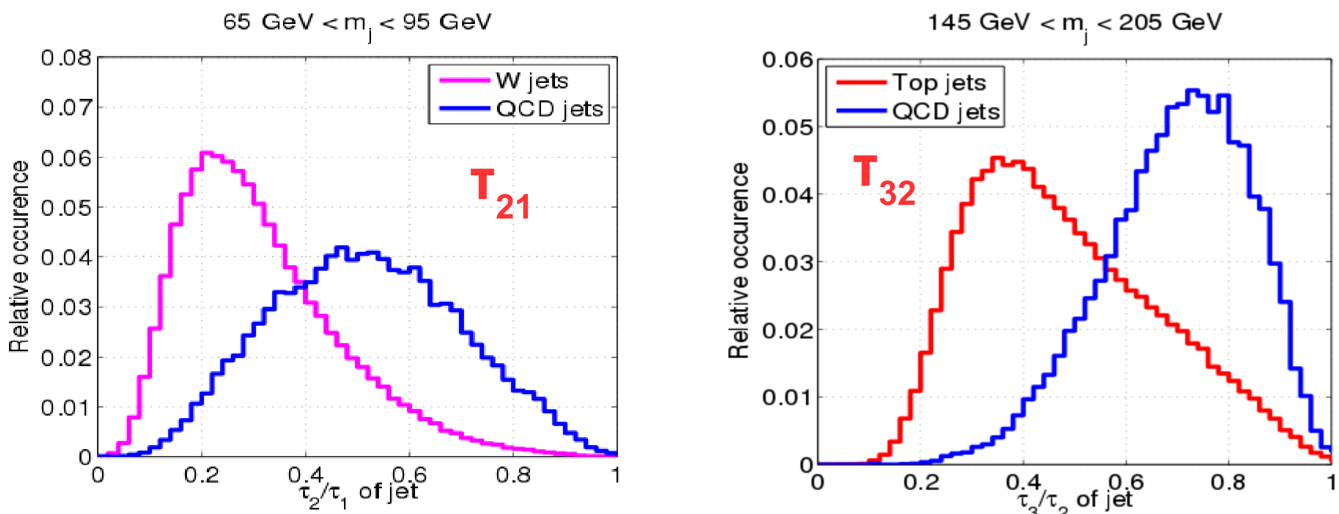
- τ_N-subjettiness - measure of the degree to which a jet can be considered as being composed of N-subjets
- $\tau_{21} = \tau_2 / \tau_1$ $\tau_{32} = \tau_3 / \tau_2$

J.Thaler and K. Van Tilburg, JHEP 1103 (2011) 015

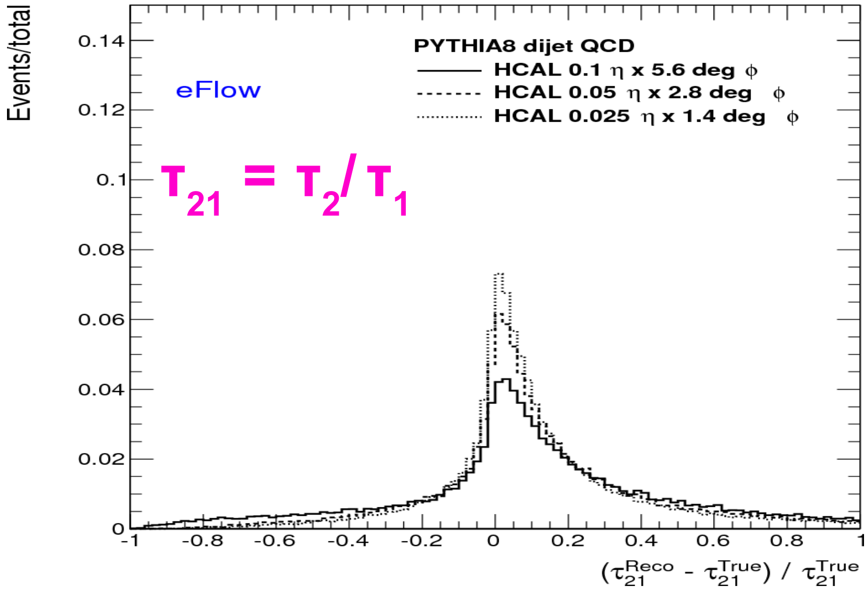
- τ_{21}**<0.3** cut reduces QCD dijet background for 2-body decays (Z/W/H)
- τ_{32} **>0.75** cut reduces QCD dijet background for 3-body decays (top)

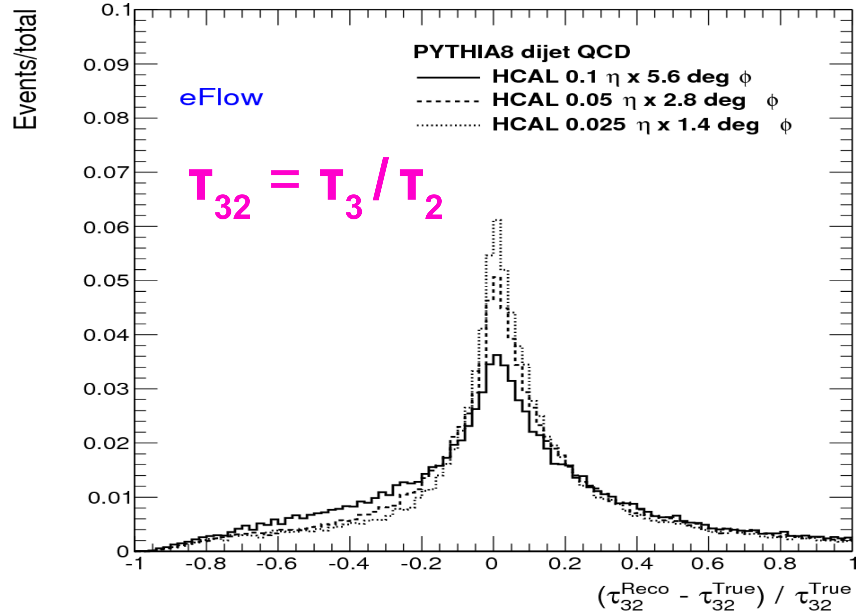
Useful for 2-body decays

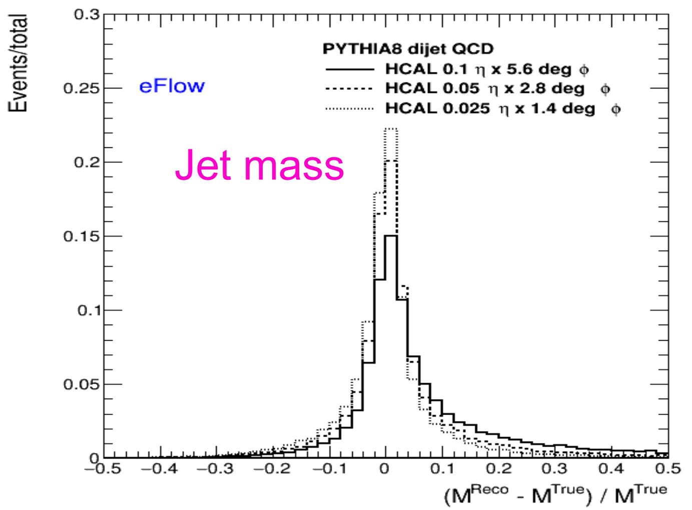
H-> $b\bar{b}$



Resolution for pT(jet)>10 TeV (HepSim+Delphes)







Decrease in RMS compared to $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$

	$\Delta\eta \times \Delta\varphi = 0.05 \times 0.05$	$\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$
tau21	18%	28%
tau32	9%	13%
jet mass	80%	120%

Large improvement in resolution for $\Delta\eta \times \Delta\varphi = 0.025 \times 0.025$

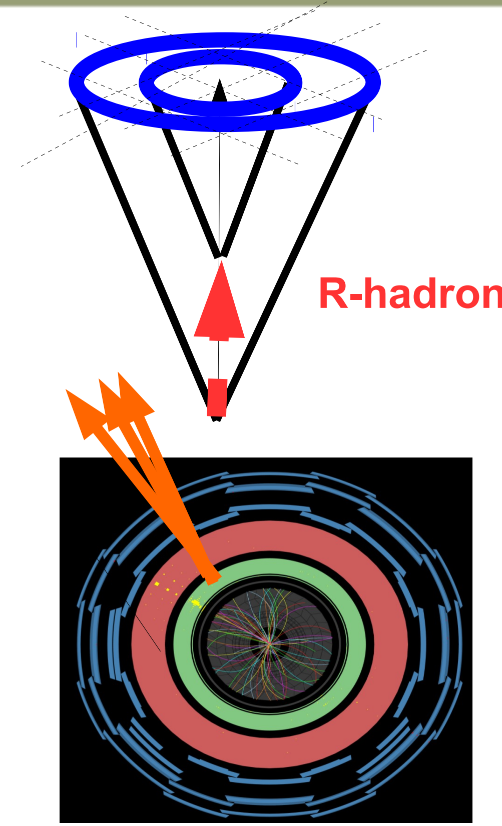
Energy range of HCAL cells

FCC HCAL cells should accommodate ~20 TeV SM jets

Dynamic range of cell readout determined by cell sizes

Large cells → large dynamic range → expensive readout

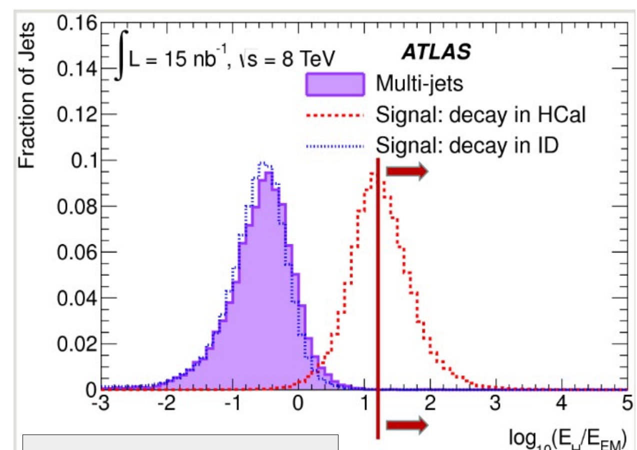
Dynamic range for cells of the existing experiments **~ 10^4**
→ Example: HCAL 0.2 GeV (muons) – 1.5 TeV (LHC jets)



Safe margin:

BSM scenario with long-lived jets for channels such as Higgs to R-hadrons:

→ Jets start close to HCAL
→ Stronger energy collimation around a few cells
→ Large energy in cells



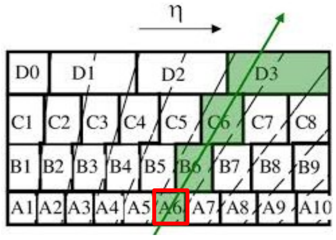
~90% jet energy in HCAL

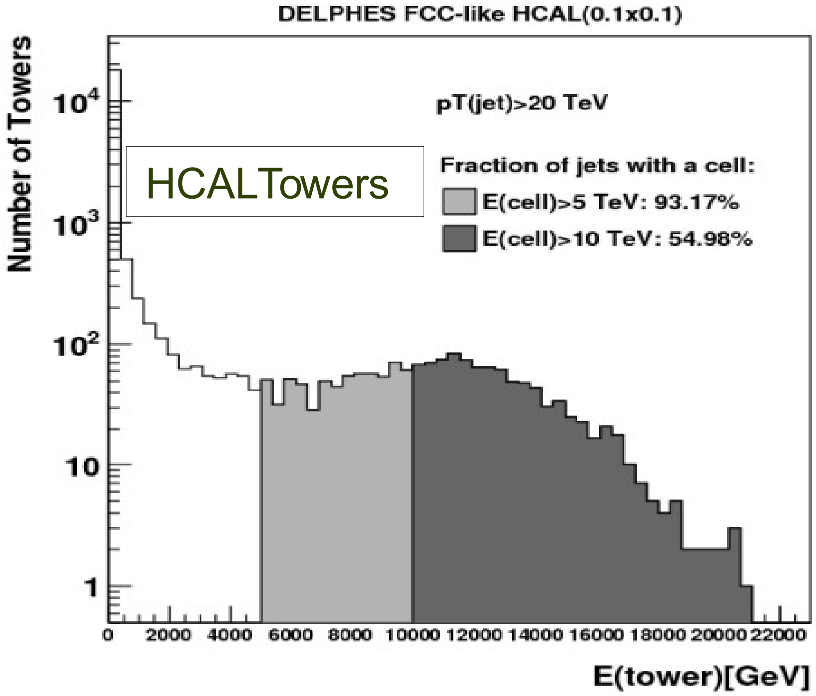
Energy range of HCAL cells using Delphes

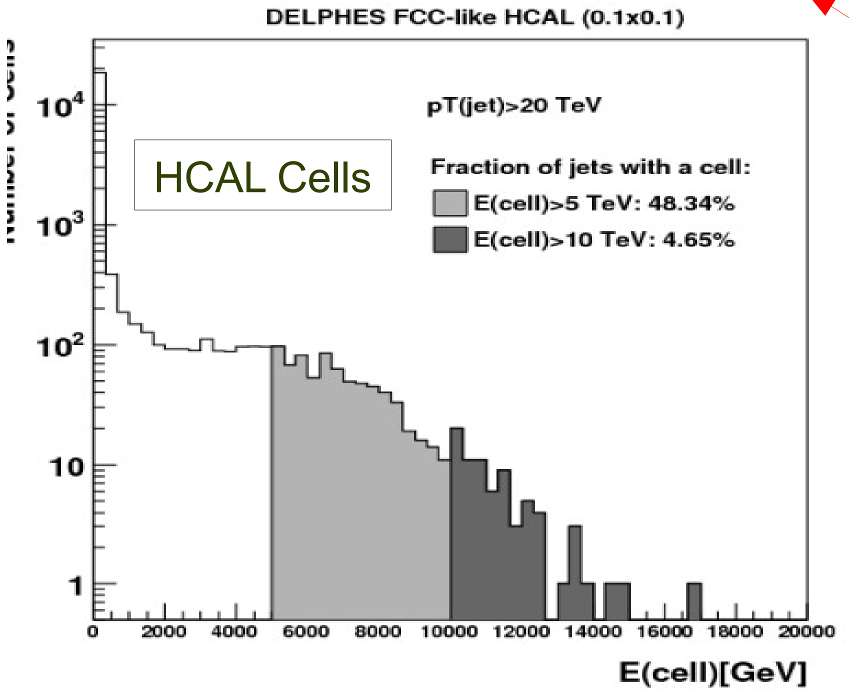
J.Dull.
ANL summer student

Energy sharing between ECAL and HCAL, and energy sharing between different layers of HCAL were tuned to ATLAS Geant4

Look at cell energy of jets using ATLAS-like HCAL with pT > 20 TeV





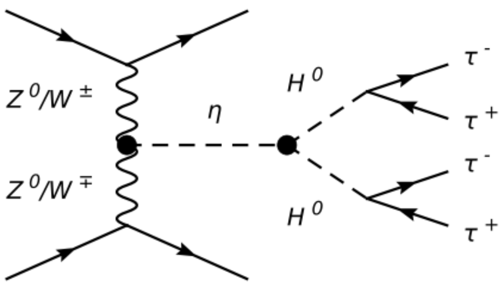


- Energy range 0.2~15000 GeV for 0.1x0.1 cells for jets above 20 TeV
- Technical challenges for readout (~10^5 cell dynamic range)

Forward η coverage

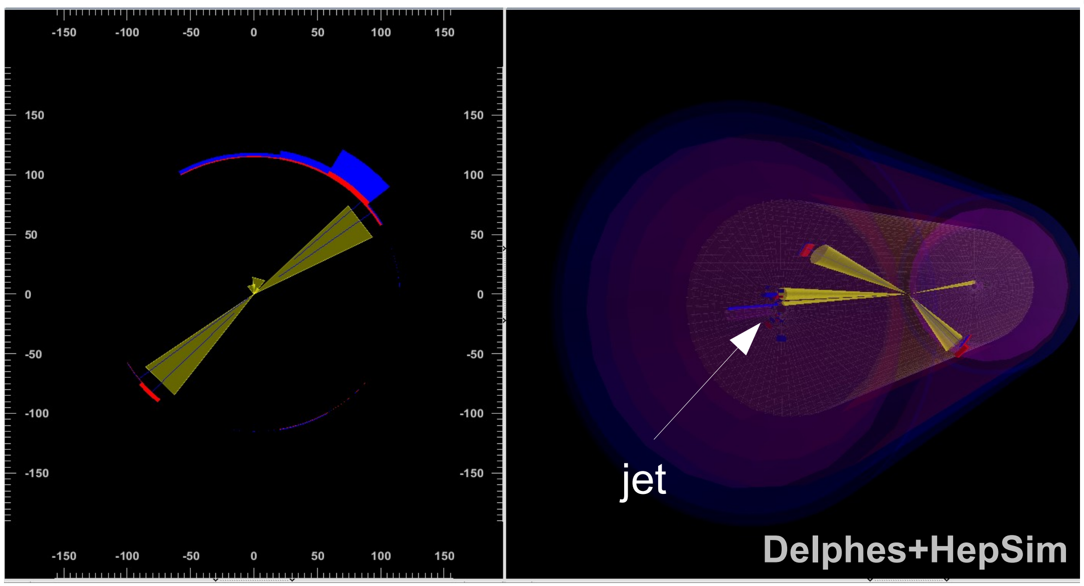
A. V. Kotwal, S.C., M.Low
Phys. Rev. D 91, 114018 (2015)

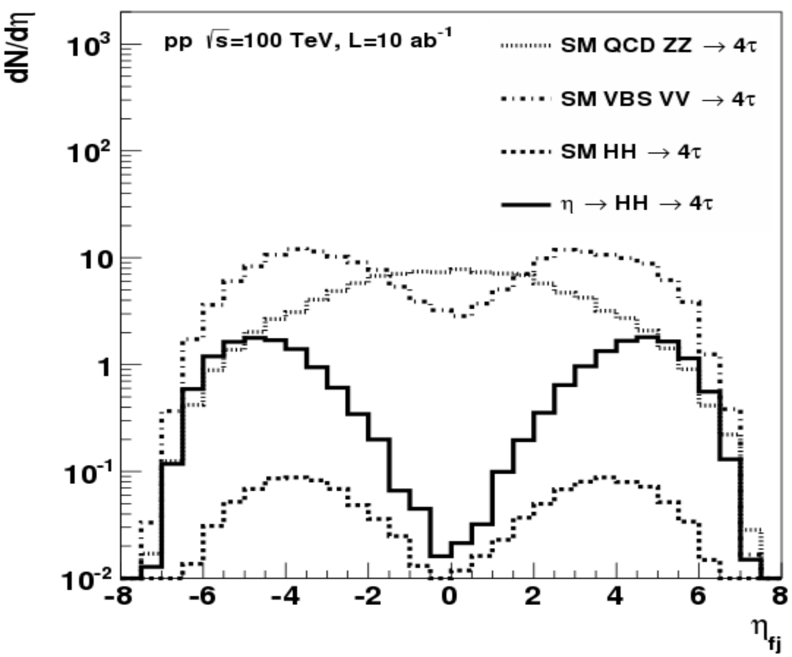
- Many SM channels benefit in opening up the η range
  - VBF-Higgs production, WW → WW, WW → HH, $t\bar{t}H$ production
- BSM channels: High-mass resonances in vector-boson scattering & Higgs decay:



h → 2H → 4 τ

~ 50% of events in the region η~4-6
Typical requirement coverage: η~6

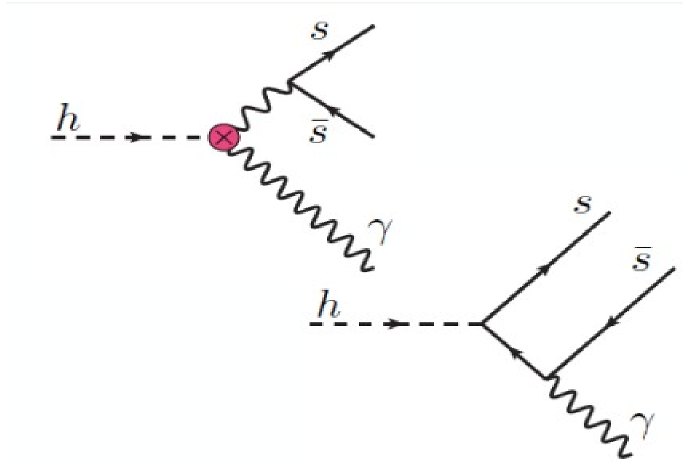




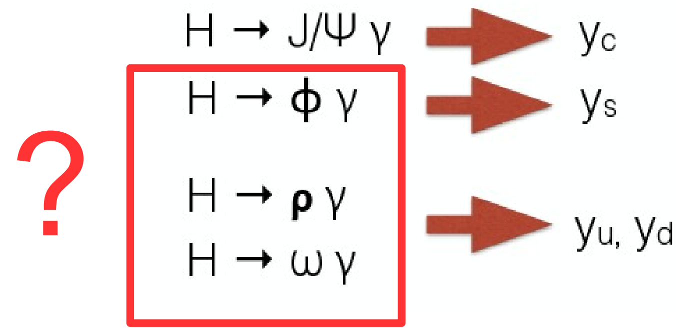
Requirements for Higgs at a 100 TeV collider. S.Chekanov (ANL)

Challenges for rare Higgs decays

- Sensitivity to u/d quark Yukawa coupling
- Example: H → φ(1020) γ where φ(1020) → K+K-



from M.Klute, FCC meeting (DC 2015)



- Using dEdX for particle identification?
  → But typical p(K) from Higgs will have ~20 GeV..
- Look at a reduced phase space p<3 GeV where the standard methods might work?
- Triggering on K+K- and photons?
  → beyond the current ATLAS and CMS capabilities

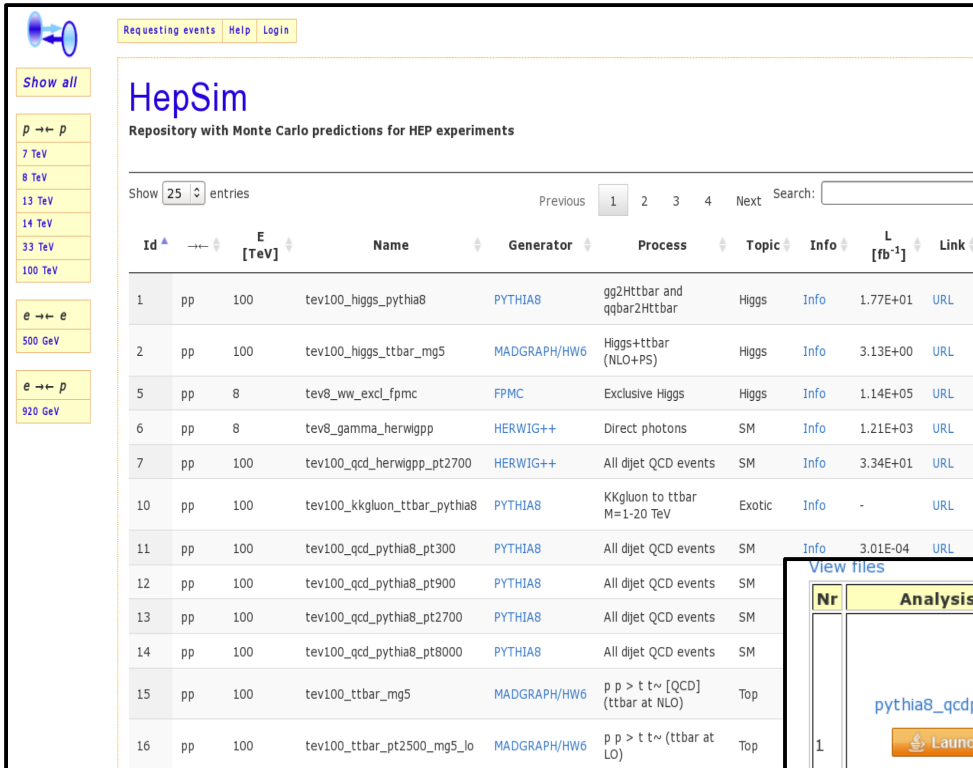
Summary

- **Many challenges.. but enough time to solve them.**
- **Tracking:**
  - ~5um pixel sizes & a lot of silicon
- **Muon spectrometer**
  - Important for high-pT Higgs
  - If CMS style, in combination with high-granular pixel tracking
- **Calorimeter:**
  - Deep HCAL (12 in depth)
  - High granularity. Cell size: ECAL <2 cm and HCAL < 5 cm?
  - HCAL resolution with constant term ~3% and below
  - Longitudinal segmentation for 3D clusters
  - Cell energy range extended by a factor 10
  - Extended coverage η~6 is designed
- **Ongoing work on full detector simulation in Europe, USA & China**

Backup

Monte Carlo samples after fast simulation used in this talk

HepSim: http://atlaswww.hep.anl.gov/hepsim/


Requesting events | Help | Login

Show all

p →← p: 7 TeV, 8 TeV, 13 TeV, 14 TeV, 33 TeV, 100 TeV

e →← e: 500 GeV

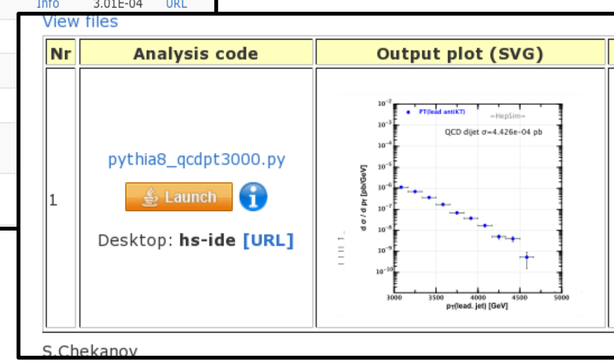
e →← p: 920 GeV

HepSim

Repository with Monte Carlo predictions for HEP experiments

Show 25 entries — Previous 1 2 3 4 Next — Search:

Id	→←	E [TeV]	Name	Generator	Process	Topic	Info	L [fb^{-1}]	Link
1	pp	100	tev100_higgs_pythia8	PYTHIA8	gg2Httbar and qqbar2Httbar	Higgs	Info	1.77E+01	URL
2	pp	100	tev100_higgs_ttbar_mg5	MADGRAPH/HW6	Higgs+ttbar (NLO+PS)	Higgs	Info	3.13E+00	URL
5	pp	8	tev8_ww_excl_fpmc	FPMC	Exclusive Higgs	Higgs	Info	1.14E+05	URL
6	pp	8	tev8_gamma_herwigpp	HERWIG++	Direct photons	SM	Info	1.21E+03	URL
7	pp	100	tev100_qcd_herwigpp_pt2700	HERWIG++	All dijet QCD events	SM	Info	3.34E+01	URL
10	pp	100	tev100_kkgluon_ttbar_pythia8	PYTHIA8	KKgluon to ttbar M=1-20 TeV	Exotic	Info	-	URL
11	pp	100	tev100_qcd_pythia8_pt300	PYTHIA8	All dijet QCD events	SM	Info	3.01E-04	URL
12	pp	100	tev100_qcd_pythia8_pt900	PYTHIA8	All dijet QCD events	SM			
13	pp	100	tev100_qcd_pythia8_pt2700	PYTHIA8	All dijet QCD events	SM			
14	pp	100	tev100_qcd_pythia8_pt8000	PYTHIA8	All dijet QCD events	SM			
15	pp	100	tev100_ttbar_mg5	MADGRAPH/HW6	p p > t t~ [QCD] (ttbar at NLO)	Top			
16	pp	100	tev100_ttbar_pt2500_mg5_lo	MADGRAPH/HW6	p p > t t~ (ttbar at LO)	Top			


View files

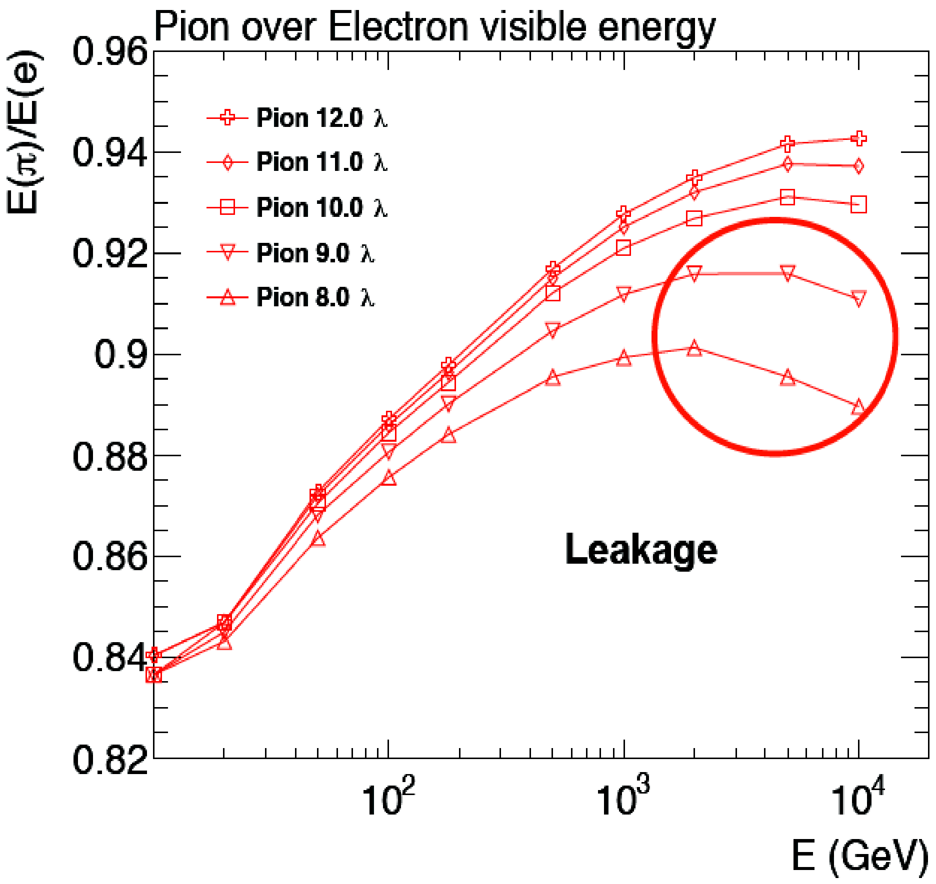
Nr	Analysis code	Output plot (SVG)
1	pythia8_qcdpt3000.py Launch Desktop: **hs-ide [URL]**	

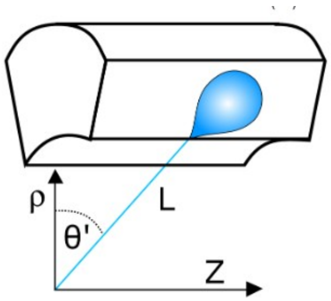
S.Chekanov

~ 10 samples with Higgs at 100 TeV

http://atlaswww.hep.anl.gov/hepsim/index.php?c=pp&e=100000&t=higgs

Estimating HCAL depth





- Geant4 TileCal inspired simulation based on FTFP_BERT
- Electrons deposit more energy (e/h>1)
- Leakage for pions when using a shorter calorimeter (ATLAS/CMS)

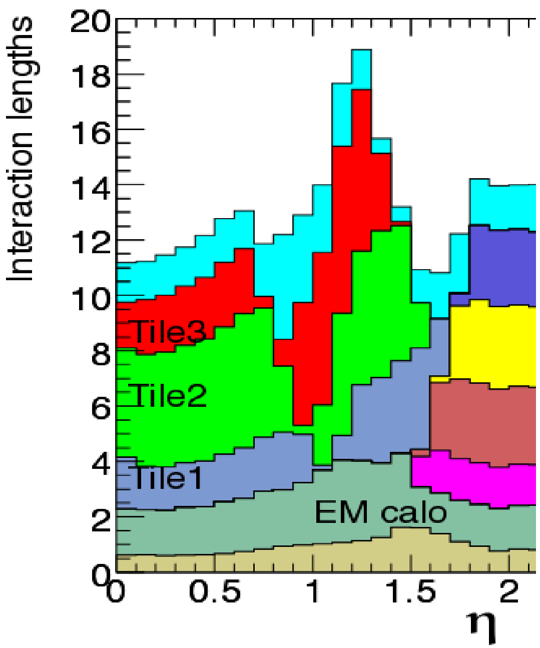
C.Solans

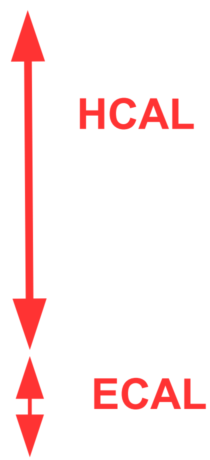
https://indico.cern.ch/event/404924/

HCAL depth considerations

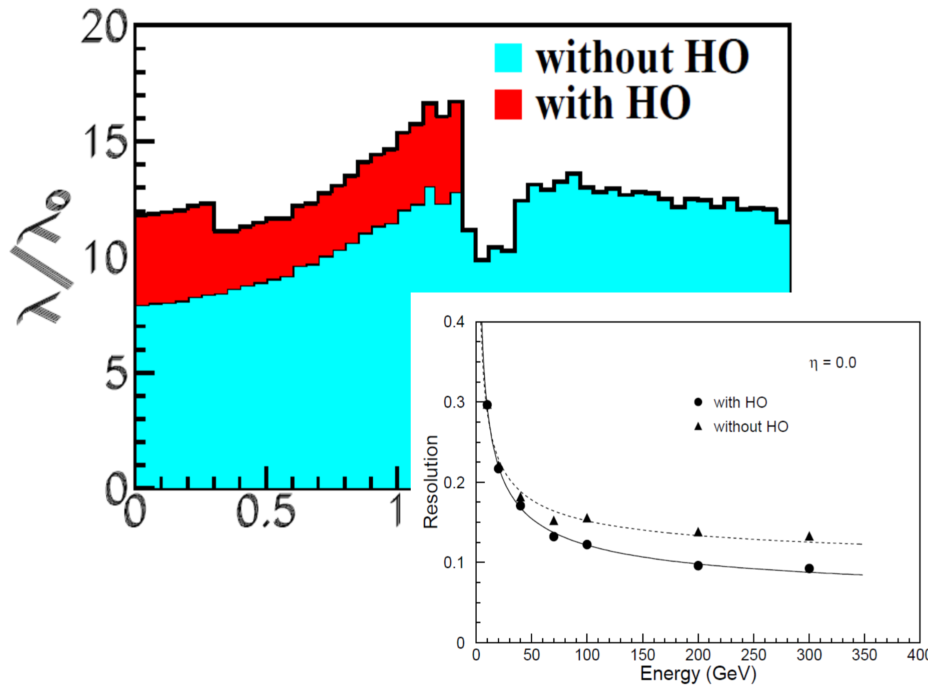
- Important for longitudinal shower development
  - fully contain the development of showers. No punch-through
- Formulated in terms of nuclear interaction length (λ)
- ATLAS HCAL active thicknesses of 7.6 λ (layers 1.9, 4.2 and 1.5 λ)
- Thickness of CMS HCAL calorimeter 5.3 λ (inside the solenoid)
  - + tail catcher (2.1 λ)

ATLAS





CMS



Calorimeter segmentation studies

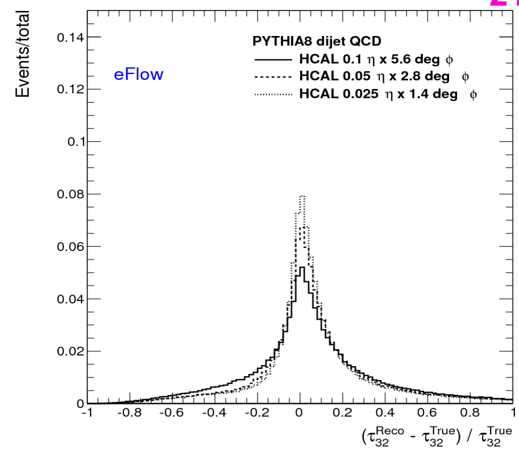
- DELPHES 3.2
- $t\bar{t}$ MG5 from HepSim
- pT(jet)>3 TeV. R=0.5
- Same ECAL.
- Reduce HCAL cells by x2 and x4

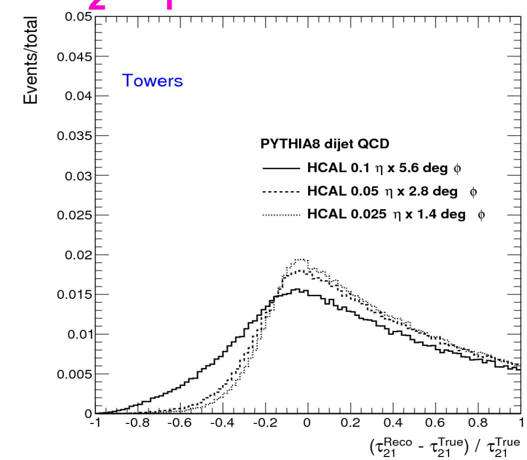
- **EFlow:**
  - Charge particles from tracks
  - Photons/electrons in ECAL
  - 60% of measured in HCAL
- **Towers:**
  - Photons/electrons in ECAL
  - 60% of other particles in HCAL

- **Improvement in resolution by 10-15% going from 0.1 to 0.05 cell size**
- **Improvement by 4-5% going from 0.05 to 0.025 cell size**

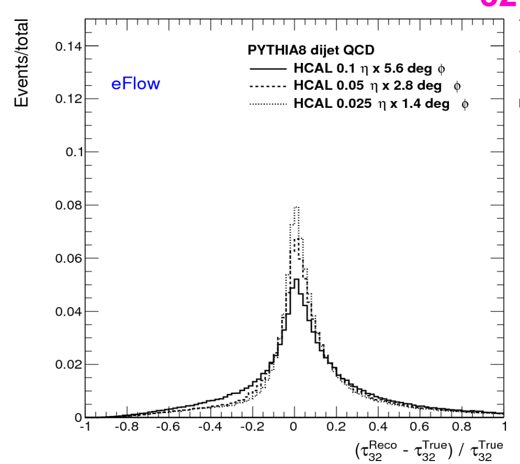
HepSim → DELPHES fast simulation

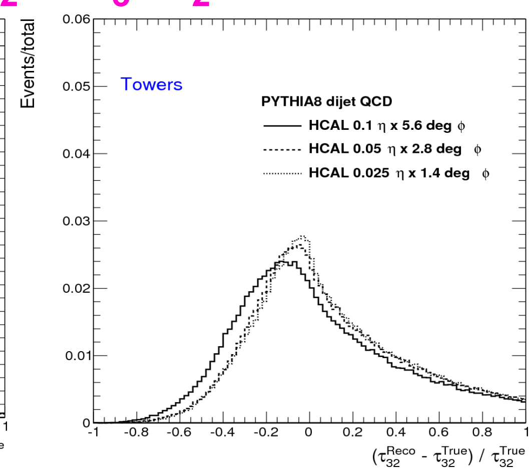
$\tau_{21} = \tau_2 / \tau_1$



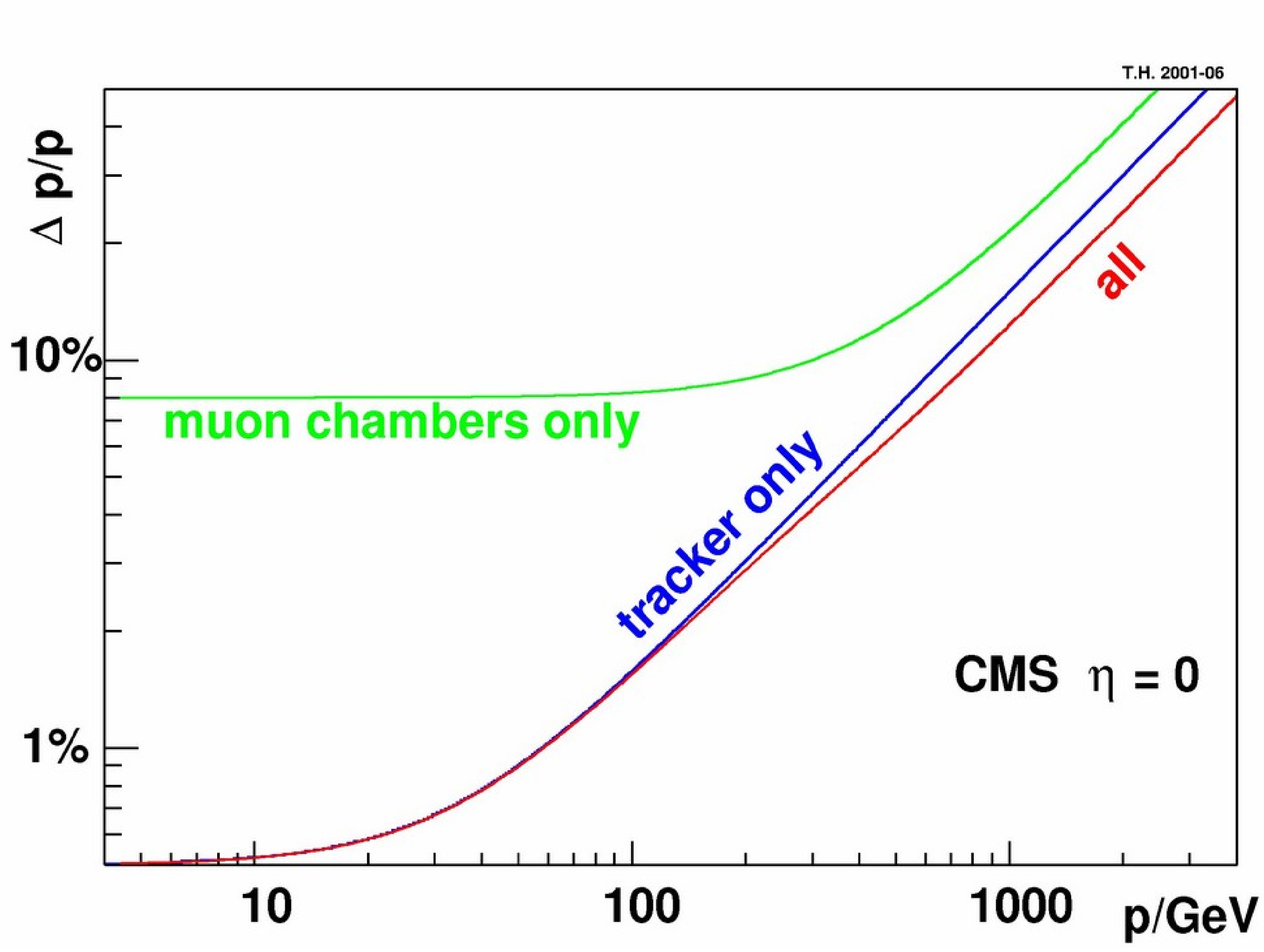


$\tau_{32} = \tau_3 / \tau_2$





CMS momentum resolution



Credits to P.Krieger